From Incubator to Space: Ten Years of Infrared Sensor Technology Development at NASA Langley

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Abstract. Over the past decade NASA Langley Research Center and its partners, with support from the Earth Science Technology Office, have been developing and demonstrating technology to measure Earth's complete infrared spectrum, from space, from within the atmosphere, and from the Earth's surface. The projects include the FIRST, INFLAME, and CORSAIR Instrument Incubator projects. The results of these projects are now aiding the development of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) satellite mission. In this talk we will give an overview of the science motivating the measurement of the complete infrared spectrum at high accuracy, the technological challenges, and the results of these several projects. There are now two new unique instruments (FIRST; INFLAME) and new components whose development is enabling an unprecedented view of Earth's climate from space within the next decade.

1. Introduction

There are three streams of radiant energy that are central to the determination of Earth's climate. The first is the energy emitted by the Sun and intercepted by the Earth; the second is the stream of solar energy reflected by the Earth and its atmosphere; the third is the stream of energy emitted by the Earth and its atmosphere. Together the energy balance of these streams, modulated by clouds, atmospheric constituents, and the Earth's surface, determine Earths' climate.

Measurements of the Earth's radiant energy have now been made from space for over 50 years since the first measurements made by Verner Suomi in 1959. These measurements have typically been of the spectrally integrated (or broadband) radiant energy with little or no spectral distinction. In the last 25 years spectrally integrated measurements of these "classic three" streams of energy have been made by a number of instruments, most recently including the Clouds and the Earth's Radiant Energy System (CERES) on the NASA Earth Observing System and the Geostationary Earth Radiation Budget Experiment (GERB) on the European Meteosat Second Generation series of satellites. These measurements provide the fundamental energetic constraints on the Earth's climate at the top of the atmosphere.

Over the past decade it has become clear that spectrally resolved measurements of the radiant components of Earth's climate system provide a wealth of information about the forcing and response of the climate system to anthropogenic and naturally occurring changes. This has led, particularly for the longwave or infrared radiant component of the climate system, to development of technologies to measure the nearly complete spectrum of radiation at the top of the atmosphere, within the atmosphere, and also from Earth's surface looking up.

In this paper we present some of the science motivating spectrally resolved measurements of the Earth's infrared spectrum. We will then describe specific projects and the new scientific instruments that have been developed, demonstrated, and utilized in scientific campaigns over the last ten years at NASA Langley. Lastly, we discuss how these efforts are leading to the development of the Climate Absolute Radiance and Refractivity Observatory (CLARREO) mission defined by the National Research Council's Decadal Survey for Earth science in 2007. Measurement of spectrally resolved infrared emission at the top of the atmosphere over the range of energetically significant wavelengths is a prime objective of the CLARREO mission.

2. Science Background

The energetically significant portion of Earth's infrared emission spectrum is between 4 and 100 micrometers (μm) or equivalently, 2500 and 100 wavenumbers. Shown in Figure 1 are several top-of-atmosphere, clear-sky infrared spectra computed for a variety of standard atmospheric conditions ranging from tropical to sub-arctic winter. Also indicated are the major gaseous species (H_2O, CO_2, O_3 and CH_4) that are responsible for absorption and emission of infrared radiation within the atmosphere. We use the vertical line at 650 wavenumbers (15.4 μm) to distinguish between the "far-infrared" portion of the spectrum and the "mid-infrared" portion of the spectrum as indicated in the Figure. The wavelength of 15.4 μm (650 wavenumbers) is chosen because there have not been spectral measurements of the far-infrared from a NASA satellite since the IRIS instruments flew on the Nimbus-3 and Nimbus-4 in 1969 and 1970.

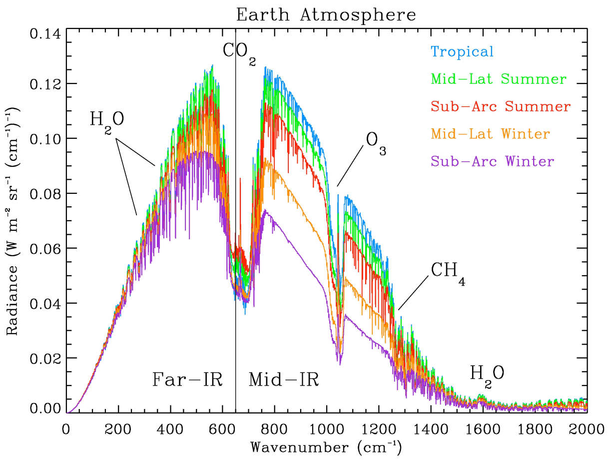

Figure 1. Earth's infrared spectrum.

The distinction between far-infrared and mid-infrared is critical. The mid-infrared spectrum is largely determined by emission in the atmospheric window between ~ 8 and ~ 12 μm and is largely responsible for cooling the planet's surface. In contrast, there is substantial absorption and emission by water vapor in the far-infrared. As is visually evident from Figure 1, a large fraction of the Earth's outgoing longwave radiation (OLR) is in the far-infrared. Approximately one-half of the OLR is in the far-infrared, while nearly three-quarters of the OLR from the atmosphere is in the far-IR. Cirrus clouds also modulate emission across the entire spectrum but have not been comprehensively characterized by measurement in the far-infrared.

The wavelength of 15.4 μm is essentially the cut-off wavelength for conventional infrared detectors such as those made from HgCdTe or InSb. In addition, for applications such as determination of temperature, moisture, and chemical composition, the mid-infrared is rich with spectral features from which these measurements can be derived. Hence, from an atmospheric sounding perspective, there has not been a technical or scientific need for measuring the far-infrared. The emerging need to accurately measure and understand climate and climate change has brought on the need to measure not only the far-infrared but in fact the entire infrared spectrum at high (< 1 wavenumber) resolution.

3. The FIRST Instrument

The Far-Infrared Spectroscopy of the Troposphere (FIRST) Instrument was proposed to the NASA Earth Science Technology Office Instrument Incubator Program in 2001 and was selected for development late that year. The goal of the FIRST project was to develop and demonstrate the technology necessary to make measurements of the far-infrared and infrared spectrum in a single instrument on a single focal plane.

FIRST is a high-throughput (0.47 cm^2 sr) Fourier transform spectrometer with a germanium on polypropylene beamsplitter. Shown in Figure 2 is the basic layout of the FIRST instrument, which is housed in a vacuum container and can be cooled to ~ 180 K in order to simulate the space environment and the lowest temperatures likely to be attained on orbit. The instrument has a scene select mirror that allows for viewing of the Earth/atmosphere scene as well as two blackbody ports for calibration.

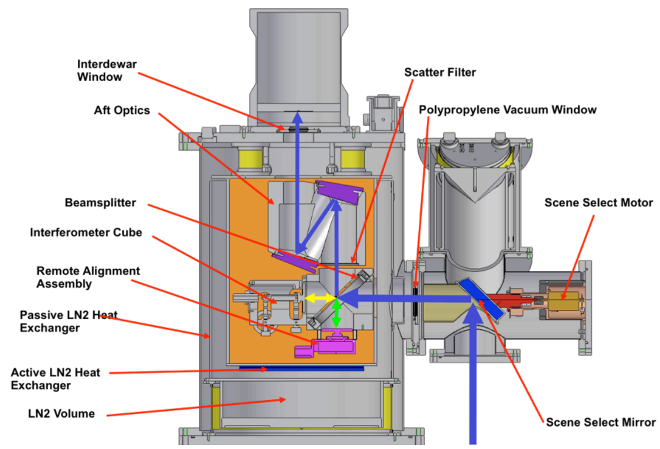

Figure 2. The FIRST Instrument.

FIRST was demonstrated on a high altitude (~105,000 feet) on June 7, 2005 from the NASA Columbia Scientific Balloon Facility in Fort Sumner, NM. The instrument operated nominally for approximately 6 hours and recorded several thousand spectra on 10 discrete detectors. Shown below in Figure 3 is the "first light" spectrum from the instrument. Curves of the Planck blackbody function at different temperatures are indicated in the figure background. The instrument succeeded in demonstrating the technology and ability to measure the infrared spectrum, including the far-infrared spectrum, from 200 to 5 μm (50 to 2000 wavenumbers).

The FIRST instrument flew again from Ft. Sumner in September, 2006, in support of validation activities associated with the "A-Train" series of satellites. The instrument operated nominally again for 6 hours at "float" altitude near 30 km. Shown below in Figure 4 is a comparison of the far-infrared spectra recorded in 2005 (blue curve) and in 2006 (red curve). There was substantially less emission recorded in 2006 and this has been traced to a lower and middle troposphere that was 15 to 20 degrees cooler in 2006.

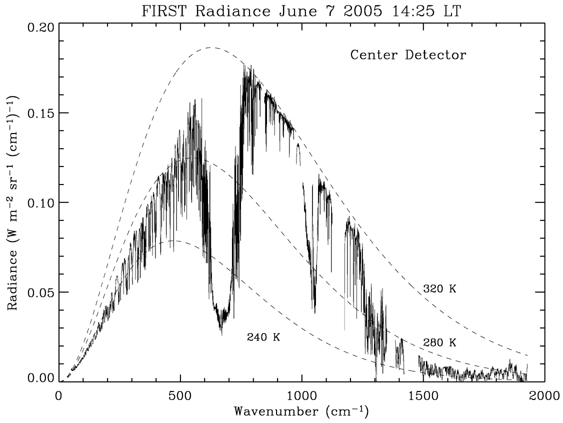

Fig. 3. FIRST-measured infrared spectrum from June 2005.

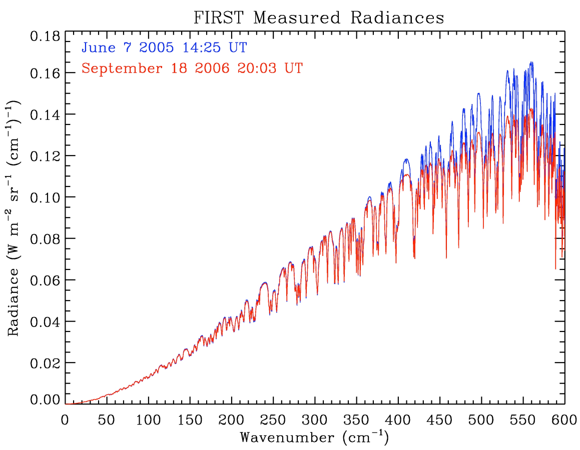

Fig. 4. Far-infrared spectra measured by FIRST in June 2005 (blue) and September 2006 (red).

The FIRST instrument has now transitioned from an "incubator" and "technology demonstration unit" to a full-fledged science instrument. Over the course of 2007 and 2008, a second blackbody was built and the scene select assembly was rotated so that the instrument could view the zenith direction and thus operate from the ground. The second blackbody operates at a different temperature from the first, offering the standard 2-point calibration for the FTS. The instrument may operate in a nadir view mode from a balloon platform or in the zenith view mode from the ground.

The modifications to enable ground operation of FIRST was to allow participation in field experiments conducted by the Department of Energy Atmospheric System Research (ASR) program. Specifically, from July to November 2009, FIRST participated in the Radiative Heating in the Underexplored Bands Campaign – II (RHUBC-II). The campaign was conducted on the top of Cerro Toco, a mountain 17,600 feet above sea level in the Atacama Desert of Chile. FIRST was operated at this altitude along with 3 other FTS instruments to record the entire downwelling infrared spectrum of Earth's atmosphere from the sub-millimeter to the near-infrared at high spectral resolution. The purpose of RHUBC-II was to conduct a radiative closure experiment, in which measurements of infrared emission spectra would be compared with calculated spectra. The inputs for the calculations are provided from radiosonde data taken simultaneously with the infrared spectral measurements. The location (and altitude) of the experiment were chosen so as to be above most of the water vapor and thus avail the spectral development of the far-infrared to be observed down as low as 200 wavenumbers.

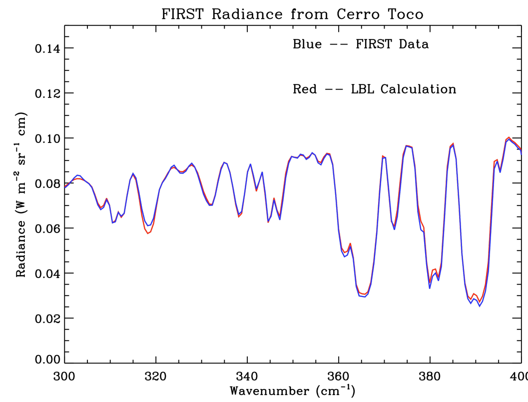

Figure 5. Preliminary comparison of FIRST and modeled far-infrared spectra from Cerro Toco in September 2009.

Shown in Figure 5 above is a spectrum between 25 and 33 μm (400 to 300 wavenumber) recorded on 5 September 2009 at Cerro Toco. The figure shows the measured FIRST spectrum in blue and the computed spectrum in red. The agreement is quite good at this preliminary stage of the analysis of the data.

In summary, the FIRST project has demonstrated technologies in FTS instruments, optical beamsplitters, and focal planes.

4. The Inflame Project

As important as the measurement of infrared spectra is at the top of the atmosphere and from the surface looking up, it is also crucially important to understand radiation fields within the atmosphere. The divergence of the net flux of radiation determines the rate at which the atmosphere heats or cools by radiative transfer. However, measuring radiative heating rates within the atmosphere is perhaps the most difficult measurement to accomplish.

The fundamental equations solved in every atmospheric model include the momentum and continuity equations and the thermodynamic equation or equivalently, the first law of thermodynamics. The main terms in the first law that must be determined are the rates of atmospheric heating and cooling due to absorption of solar radiation and emission of infrared radiation. The radiative heating rate dT/dt is determined from the expression

$$\frac{dT}{dt} = \frac{-1}{\rho C_p} \frac{dF_{net}}{dz}$$

where ρ is atmospheric density, c_p is the heat capacity at constant pressure, and F_{net} is the net radiative flux at altitude z. The net flux is simply the difference between the energy flowing upward and downward through an aperture of unit area, or $F_{net} = F\uparrow - F\downarrow$. The change in net flux with altitude is the net flux divergence, dF_{net}/dz, and is proportional to the rate dT/dt at which radiation heats or cools the atmosphere. The net fluxes are usually separately determined for the visible (solar) and the infrared (thermal) parts of the spectrum. Determining the net radiative flux, the flux divergence, and heating rates remains a fundamental goal of many NASA projects. For example, the Clouds and the Earth's Radiant Energy System (CERES) project presently operating on the EOS Terra and Aqua satellites produces net flux and flux divergence data products for several broad atmospheric layers.

The In-situ Net Flux within the Atmosphere of the Earth (INFLAME) project was selected for development by the Instrument Incubator Program. The project has being carried out at the NASA Langley Research Center. Our goal is to measure the shortwave and longwave net flux with sufficient stability to derive tropospheric heating rates in 1 km layers that are accurate to within 10%. This requires measuring the net flux with a stability of 0.2% per km and 0.8% per km in the shortwave and longwave spectral regions, respectively. It is important to note that while measuring the net flux divergence requires that the instrument response be very stable, it does not require a similar level of absolute accuracy in measuring the net flux. If the calibration errors are stable and independent of altitude then the relative uncertainty in the net flux divergence will be no greater than the relative uncertainty in the net flux measurement.

The INFLAME instruments measure the net flux by using a low-resolution Fourier transform spectrometer (FTS) to observe the upward and downward flux simultaneously using the two inputs of the same instrument. The two complementary outputs of the FTS can be transformed to produce spectra proportional to the difference between the two inputs.

The net flux will be measured directly in the atmosphere by deploying the INFLAME instruments on a Lear Jet. The instruments will be mounted in the wing tip tanks. The aircraft will slowly ascend from near the surface to approximately 40,000 feet in altitude, recording the profile of net flux. As indicated by Equation 1, the derivative of the vertical profile of net flux gives the rate at which the atmosphere is heated.

INFLAME employs one spectrometer for measuring net flux in the visible portion of the spectrum to determine heating rates due to the absorption of solar radiation and one spectrometer for the infrared to determine the radiative cooling rates due to emission. Using two separate spectrometers allows us to optimize the mirror coatings, beamsplitter, and detectors for each wavelength range.

Fig. 6. One INFLAME instrument mounted in a LearJet wing tip pod just prior to flight demonstration in January 2010.

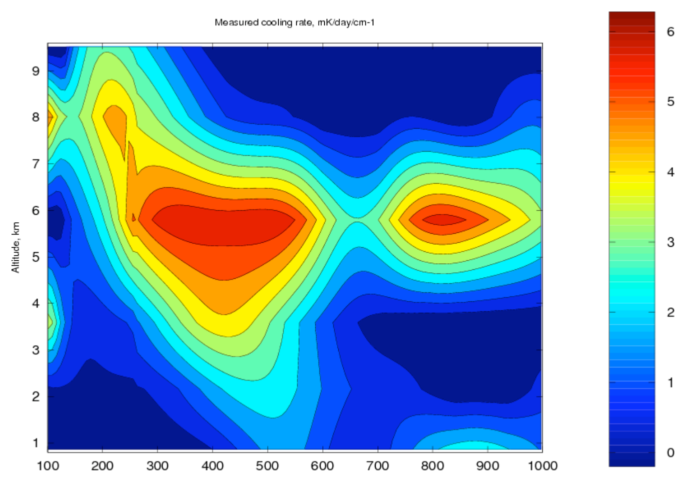

Fig. 7. Measured infrared radiative cooling rate from the demonstration flight of INFLAME in Janaury 2010.

Shown above in Figure 6 is one of the INFLAME instruments in the wing tip pod of a LearJet. The other instrument is mounted in the opposite wing. INFLAME successfully flew on January 5 2010 from Patrick Henry Field in Newport News, VA. The infrared instrument performed nominally. Shown in Figure 7 is the spectral infrared radiative cooling rate (mK day^{-1} cm) measured by INFLAME. The flight took place over 2.5 hours just off the Virginia coastline. Figure 7 is the first measurement ever of the spectral infrared radiative cooling rate in the atmosphere.

The INFLAME project successfully completed in 2010 and has met its goals of developing the technology to measure the spectral radiative heating and cooling rates within the atmosphere. The INFLAME instruments are unique and are ready for deployment to science campaigns, just as the FIRST instrument is.

5. The CORSAIR Project

With the release of the Decadal Survey and the nominal high-level requirements for the mission given in the Introduction above, it is clear that there are several areas of technology that need to be developed to achieve the goals of the mission, in addition to those already developed under FIRST and INFLAME. Specifically, sensitive detectors for the far-IR that do not require cryogenic cooling are required. In addition, radiance standards that are SI-traceable in the far-IR must be developed, as must techniques to monitor the emissivity of the on-board calibration blackbodies in the far-IR.

To address these needs Langley Research Center partnered with industry (Raytheon Vision Systems; Space Dynamics Laboratory; and ITT, Inc.) and other government laboratories (JPL, NIST) to develop the Calibrated Observations of Radiance Spectra from the Atmosphere in the far-Infrared (CORSAIR) proposal for the Instrument Incubator Program opportunity solicited by NASA in 2007. The CORSAIR proposal was selected in April 2008 and the team is now preparing to implement the proposed work effort. We will touch briefly here on the proposed scope of work in the CORSAIR effort.

D.1 Warm detectors

To meet the anticipated CLARREO measurement requirements on a small satellite will require detector technologies that do not need cryogenic cooling. Current far-IR detection technologies (e.g., silicon bolometers) typically require cooling to liquid helium temperatures (4 Kelvin or lower) and are not viable options for long-term spaceflight missions due to the absence of cryocoolers. The volume of liquid helium required for passive cooling to 4 Kelvin is also prohibitive. Current off-the-shelf technologies, e.g., pyroelectric detectors have relatively low responsivity and tend to be susceptible to acoustic and microphonic effects. They are also known to be hygroscopic.

We have proposed under CORSAIR to develop and demonstrate a new class of detectors for the far-IR. Specifically, Raytheon Vision Systems of Santa Barbara, CA has been developing antenna-coupled devices for detecting infrared radiation at terahertz (THz) frequencies (1 THz corresponds to a wavelength of 300 μm). The objective of this task for CORSAIR is to extend the technology to operate into the far-infrared at frequencies as high as 20 THz (15 μm). This is achieved by a combination of increasing the length of the antenna arm and modifying the Schottky diode that forms the detector element in the device. The devices operate at room temperature. The effort leverages substantial prior investment from other government agencies and Raytheon internal research and development sources. It is anticipated that the sensitivity of these devices will be 100 times larger than that of conventional pyroelectric devices as measured in the specific detectivity of the detector. The detectors will undergo comprehensive testing and evaluation in the FIRST instrument at Langley. These tests will occur during the third year of the effort and provide demonstration of the technology at TRL 6.

D.2 Calibration Standards in the Far-IR

Perhaps the single facet that sets CLARREO apart from other Earth science missions is the requirement to make radiance measurements of the Earth's infrared spectrum that are traceable to international measurement standards. To achieve this requires that international standards (referenced to the SI system) exist for laboratory calibration, and that the measurement can be shown to be SI-traceable on orbit for the duration of the mission.

In the far-IR there are presently no SI radiance standards. An objective of the CORSAIR proposal is to establish these. Space Dynamics Laboratory, working with the National Institute of Standards and Technology and the Langley Research Center will establish these and will develop a prototype blackbody radiance source for the CLARREO mission that is SI-traceable in the far-IR. This part of the CORSAIR team will also develop and demonstrate techniques to monitor the emissivity of the blackbody on orbit, something that is essential to demonstrating continued on-orbit SI-traceability.

D.3 High efficiency beamsplitters

Although the FIRST project demonstrated beamsplitter technology for the far-IR, and although the FIRST instrument demonstrated an ability to measure essentially the entire infrared spectrum, there are regions in the FIRST spectra where absorption features in the beamsplitter substrate are sufficiently large to substantially degrade the measurement. As defined in the decadal survey, the CLARREO mission must measure the spectrum continuously between 5 and 50 μm, or equivalently, between 2000 and 200 wavenumbers (cm^{-1}). To meet this requirement, a high efficiency, broad bandpass beamsplitter will be required to span the required range of wavelengths. ITT, Inc. and Langley are working jointly on the design and testing of different broad bandpass beamsplitters.

6. Towards The CLARREO Mission

In 2007, the United States' National Academy of Science, at the request of NASA, NOAA, and the US Geological Survey, released a report entitled "Earth Science and Applications from Space: National Imperatives for the Next Decade and Beyond" [http://www.nap.edu/catalog/11820.html; *National Academy Press*]. The first of its kind for Earth science, this "decadal survey" recommended a series of space missions for NASA and NOAA to undertake over the course of the next decade to further our knowledge of the Earth system. Along with the missions themselves, the decadal survey provided a notional schedule for implementation of these missions. Among the first set is a mission called the Climate Absolute Radiance and Refractivity Observatory or "CLARREO." A primary objective of the CLARREO mission is to improve our knowledge of climate change through the measurement of the Earth's infrared emission spectrum at very high accuracy and traceable to the international system of units (Système International or SI) and radiometric standards. An additional objective of the CLARREO mission is to make measurements that can be used to cross-calibrate other orbiting sensors. The CLARREO mission envisions a series of very accurate and stable interferometers (Fourier Transform Spectrometers, FTS) measuring the infrared spectrum at high accuracy and stability. The nominal measurement requirements from the decadal survey are:

- Spectral Range: 5 to 50 μm (2000 to 200 cm^{-1}).
- Spectral Resolution: 1 cm^{-1}
- Instantaneous Field-of-View: < 100 km
- Absolute accuracy: 0.1 Kelvin
- SI Traceability: Entire spectrum

The FIRST, INFLAME, and CORSAIR projects are provide much of the necessary technology to achieve the CLARREO objectives, through the development of unique instruments and specialized components for Fourier Transform Spectrometers.

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